Aeroacoustic investigation of a flow pipe with a small cavity using the lattice Boltzmann method.

Ulf Kristiansen, Daniel Mazzoni, Anders Bakke Krogvig

Aeroacoustic investigation of a flow pipe with a small cavity using the lattice Boltzmann method. *

Ulf Kristiansen[1], Daniel Mazzoni[2], and Anders Bakke Krogvig[1]

[1]Acoustics Research Center, Department of Electronics and Telecommunications, Norwegian University of Science and Technology, O.S. Bragstads plass 2b, Trondheim 7491 Norway
[2]Laboratoire de Mechanique et d'Acoustique, UPR CNRS 7051, 31 chemin Joseph Aiguier, 13402 Marseille Cedex 20, France

Abstract

The lattice Boltzmann method has been used to study the flow and associated sound generation in a flow pipe having a cavity close to the pipe's entry section. The study is an initial survey on the use of this method for such an aeroacoustic problem and does not represent a detailed parametric investigation. It is shown that vortices are formed by flow separation at the pipe's inflow end and that they interact with the cavity geometry. A basically reactive sound field is generated in the modeled geometry.

1 Introduction

In an earlier communication [1] we reported results from measurements on flowpipes having a single small cavity close to the inflow end. The experimental pipes' lengths were in the range 0.5–1.5 m long while their diameter was kept constant at 43 mm. The cavity length could be adjusted between 0 and 20 mm. For the parameter range of our investigation it was found that a pipe's longitudinal, open–open, acoustic modes could be strongly excited. For a given pipe length, the strength and frequency of the dominating mode was found to depend on flow velocity, cavity length, cavity depth, and the distance from the pipe opening to the cavity (the upstream length). The pipe would only sound for upstream lengths between certain limits. It was also found that the excitation depends on the sharp edge at the pipe's inflow end; smoothing the pipe entry by for example modeling clay made the pipe tones disappear. A conclusion is therefore that flow separation at the pipe's entry section plays an important part in the sound generation for our system. Later measurements indeed suggest that the total distance between the pipe's entry section and the downstream cavity edge, the number of vortices along this distance, and their convection speed, are important parameters for optimal excitation of the pipe-modes.

Many studies exist on the interaction of an unstable cavity shear layer and a resonant acoustic system, for instance an open–open pipe containing a cavity, or a fluid flow grazing a Helmholtz resonator. In such situations the two oscillating systems might interact and produce high whistling tones, [6, 7, 8, 9]. In a recent thesis by Nakiboglu, whistling caused by a single cavity in a finite length open–open flow pipe was studied in detail [2]. The cavity was placed at different positions within the pipe (close to the inflow end, the outflow end, or in the middle) and subjected to a grazing flow. For such flows it has earlier been demonstrated that the shear layer might curl up to form distinct vortices and traverse the cavity with velocities related to

*Paper presented at the 35^{th} Scandinavian Symposium on Physical Acoustics, Geilo, Norway 29 January - 1 February 2012

the free stream velocities in the pipes. A vortex will form at the upstream edge of the cavity at the moment the acoustic particle velocity vector starts pointing in the stream-wise direction. Such a vortex will, when it approaches the downstream edge, generate acoustic power by an interaction with the acoustic field. Nakiboglu found good agreement between his experimental results and numerical simulations combining vortex sound theory [3] and incompressible calculations based on Fluent.

For the present simulation the cavity is close to the inflow end of the pipe. The flow separates from the pipe wall at the sharp edges at the pipe's inflow end and therefore reaches the cavity in a different state than was considered in Nakiboglu's thesis. The object of our study has been to investigate the capabilities of the lattice Boltzmann program Palabos to study such aeroacoustic problems, and to draw some qualitative conclusions from the results. No detailed parametric study has yet been undertaken.

2 The model

Our model is a two-dimensional one, and we made use of the Palabos software for the computations, suitable for calculations of slightly compressible fluid flows at low Mach numbers. The Lattice Boltzmann method was implemented using a D2Q9 lattice [5]. The geometry of our system was kept as simple as possible and is shown in Figure 1. Two pipes are connected at the position of $x = x_1$. The narrow pipe extending to the right has a cavity at some distance from this section, (the flow entry section). The corners at the pipe's inflow end and the leading and trailing edges of the cavity appear sharp on the drawing, but are in fact slightly rounded (the radius of curvature is 4% of the cavity pipe's diameter). Palabos uses non-dimensional units, for details see [5]. A Reynolds number, here based on the diameter (height) of the pipe containing the cavity and the flow velocity in this pipe, must be given. In Palabos, boundary conditions pertain to the basic flow, specific acoustic conditions are difficult to implement at this stage. The

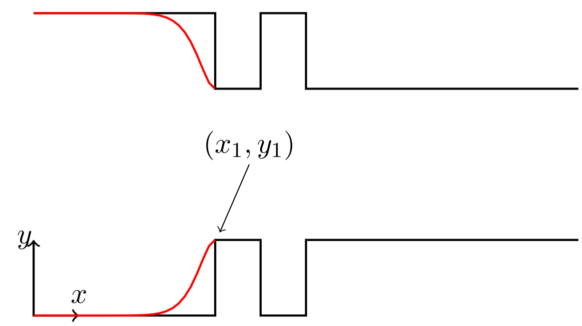

Figure 1: The two-dimensional geometry, the red lines (equation 1) defines the initial flow confining region.

complete black lines in figure 1 are treated as so-called "bounce back" nodes which correspond to hard walls (see the Palabos manual [5]). The section at $x = 0$ is also defined as a "bounce back" wall. The outlet of the small pipe to the right is given an "outflow" condition defined as a zero gradient condition for all velocity components. As will be seen in the results section, the generated acoustic modes appear to be caused by homogeneous boundary conditions, and will consequently only be damped by the viscosity of the fluid.

To initiate the model, a steady flow has to be described for the system. To join the flows in the wide and narrow pipes, the initial flow was assumed to be confined within the region marked by the red lines in Figure 1 and described by Equation 1.

$$y = \frac{y_1}{2}(1 + \sin(\pi(\frac{x}{x_1})^6 + 0.5)) \tag{1}$$

For the initial velocity profile, a 1/7 power law turbulent profile was chosen [4] for the whole domain.

2.1 The dimensions

Referring to Figures 1, 2, 3, and 4 the "pipe" is the domain located in the region $x \geq x_1$.
The domain is resolved into 600 x 1800 cells.

Parameters of the physical system :
Size of the total domain: 6 cm $\times$ 2 cm
Length of the pipe: $L_{\text{tot}} = 0.04$ m
Pipe inside diameter: $d = 0.01$ m

Length of the cavity: $L_c = 0.005$ m
Height of the cavity: $h = 0.005$ m
Sound speed: $c_0 = 340$ m/s
Fluid velocity on the axis of the pipe: $u_0 = 10$ m/s
Kinematic viscosity of the fluid (air): $\nu = 0.000015$ m^2/s
Reynolds number based on the diameter of the pipe: $Re = \dfrac{u_0 d}{\nu} = 6667$.

Parameters in Palabos units :
The speed of sound in the dimensionless lattice Boltzmann system is $c_{\text{LB}} = 1/\sqrt{3}$. The fluid velocity in the lattice Boltzmann units is given by the invariance of the Mach number in both the physical and the lattice Boltzmann system of units:

$$u_{\text{LB}} = u_0 \frac{c_{\text{LB}}}{c_0} = 0.01698.$$

In order to ensure stability of the numerical simulation the Reynolds number was reduced to $Re = 5800$.

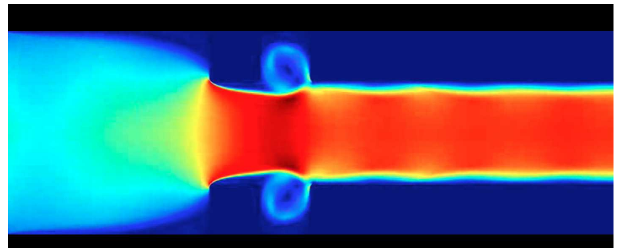

Figure 2: Snapshot of velocity simulation, Re=5400.

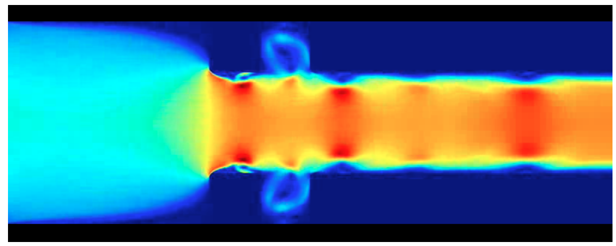

Figure 3: Snapshot of velocity simulation, Re=5800.

3 Simulations

Figures 2, 3, and 4 show snapshots of flow simulations for three different situations. Simulation films are found as the .mpeg films simulation2, 3, and 4. For the simulation presented in Figure 2, the axis velocity was reduced to 8 m/s. In the present case the cavity length and depth are equal to half the pipe diameter. *i.e.* in physical measures the pipe diameter is 10 mm and the cavity length and depth 5 mm. The upstream cavity edge is one cavity length downstream of the pipe's entry surface for figures 2 and 3, and two cavity lengths for Figure 4. It is the velocity norm which is plotted in the figures.

We see that the sharp corner at the pipe's inflow end causes the flow to separate and further to result in a clear flow circulation inside of the cavity. Figures 3 and 4 also indicate vortex structures in the separated shear layer. This is further investigated in the next section. It is also seen from figure 4 that a drastic rounding of one of the pipe's entry edges causes the flow not to separate, and only result in a weak flow circulation inside of the cavity. In connection with this it is interesting to note that rounding the entry edges of the experimental pipe described in reference 1 by modeling clay, stopped the whistling in the pipe.

3.1 A close up for a 10 mm long and 10 mm deep cavity, vorticity calculations

In a special part of the study we investigated in more detail the behavior of the vortices arriving in the cavity region for one particular flow/geometry

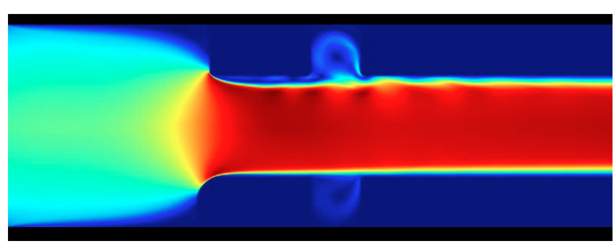

Figure 4: Snapshot of velocity simulation, Re=5800, rounded lower entry edge.

configuration. We have zoomed in on a larger cavity, *i.e.* 10 mm long and 10 mm deep, and plot the vorticity in the system. 8 pictures are presented at equal time intervals as Figures 5 and 6. Our modeling is based on a 12 cm long pipe. From the pictures, and the films vorticity1.avi and vorticity2.avi, we see the vortices approaching the cavity from the left. Traveling across the cavity the vortex is influenced by the large cavity circulation. Part of the cavity flow is seen to inject itself between two vortices and rotate the leading vortex about 90 degrees. This vortex is then seen to hit the downstream cavity edge where it divides in two. One part becomes part of the cavity circulation, and one part is seen to continue downstream. The film vorticity2.avi is based on the same calculation as vorticity1.avi, but the color scale is used differently in order to better observe the behavior around the downstream cavity edge.

3.2 The acoustic field

Palabos generates data for the velocity and density variations in the fluid. The acoustic pressure can further be obtained by multiplying the fluctuating density by the square of the speed of sound. For the measurements presented in this section the "pipe" has a length of 6 cm and the the system is meshed by 500 x 2000 cells. Figures 7 and 8 show an example for the time plots of density and x-direction velocity obtained at the entry section of the pipe. It is seen that there is a basic periodic fluctuation in the system, with superposed higher frequency signals. Note that for the dominant oscillation, the x-direction velocity is around $\pi/2$ radians out of phase with the pressure as is expected for a standing acoustic wave. A typical pressure spectrum is shown in figure 9, The main peak at the low end of the spectrum has a pressure distribution as shown in figure 10. It has the appearance of a quarter-wave acoustic resonance in a closed - open system. This resonance is a possibility in our model considering the imposed boundary conditions. The second highest peak has a pressure distribution as shown in figure 11. In physical units, taking the quarter-wave frequency of the system (calculated

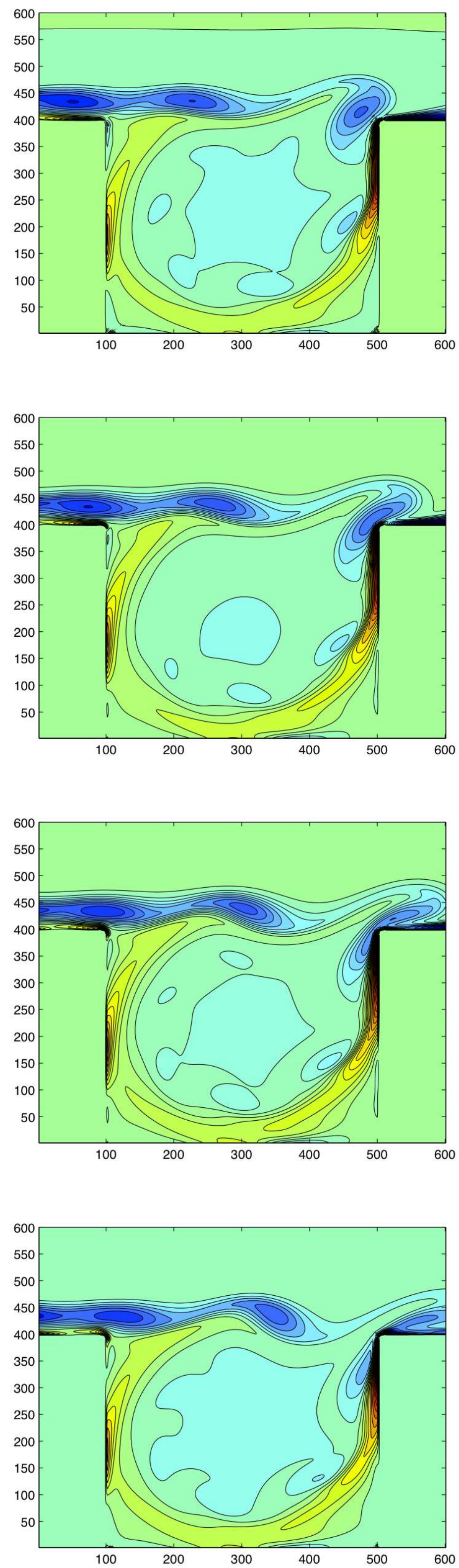

Figure 5: Vorticity distribution of the flow interacting with a cavity: 4 first plots in a series of 8 taken at equal time intervals for one period.

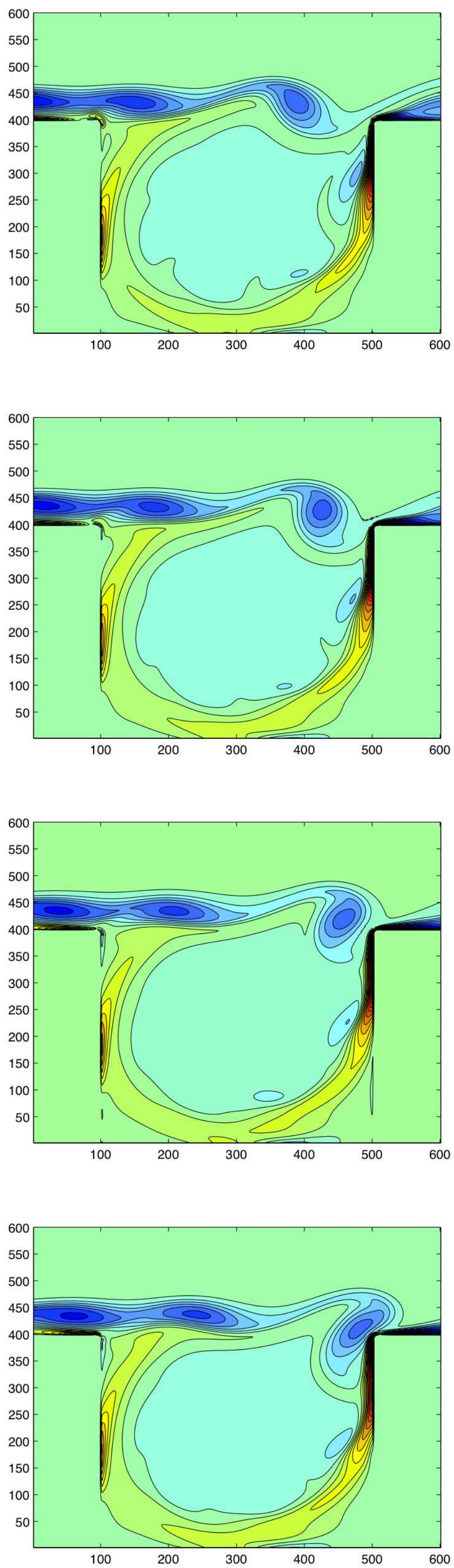

Figure 6: Vorticity distribution of the flow interacting with a cavity: 4 last plots in a series of 8 taken at equal time intervals for one period.

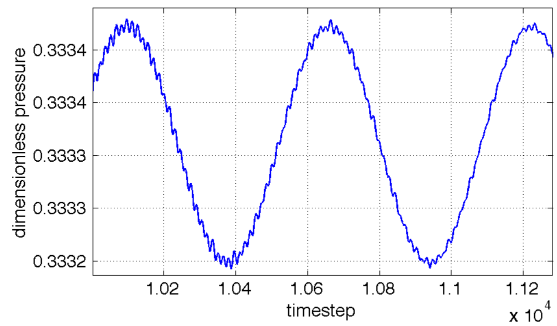

Figure 7: Pressure calculated at the pipe's inlet section.

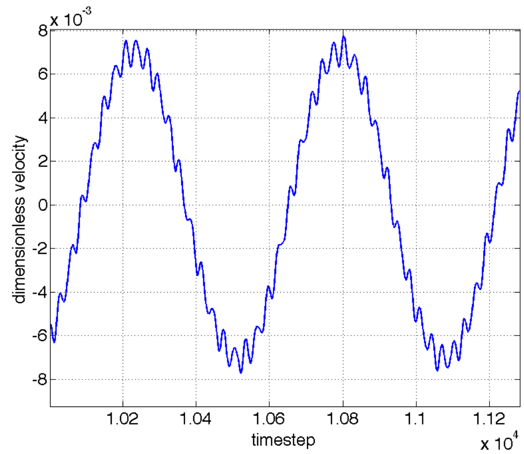

Figure 8: Fluctuating part of the x-direction velocity calculated at the pipe's inlet section.

by a finite element program for the given geometry, but no flow, to be 866 Hz), the flow velocity, which equals 10 m/s, and the cavity length (*i.e.* 5 mm) as the significant parameters, the Strouhal number for the motion is $St = f \cdot L_c/u_0 = 0.43$. Figure 12 present a limited study on the magnitude of the principal acoustic mode as a function of cavity length.

4 Conclusion and further work

It was demonstrated that the lattice Boltzmann method is capable of modeling the coupling of acoustics and aerodynamics in a flowpipe situation. In the present case, instabilities in the form

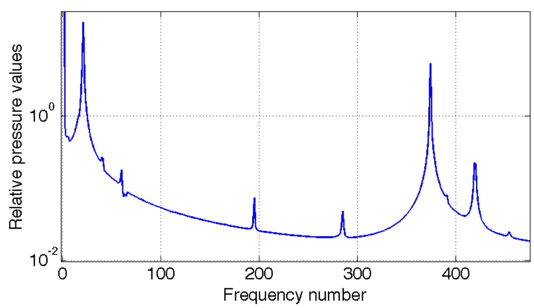

Figure 9: Spectrum of the system oscillation

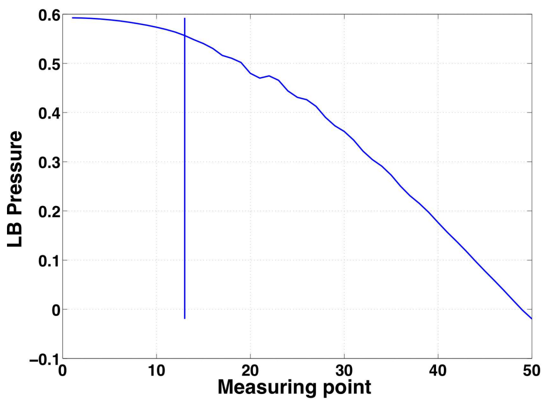

Figure 10: Pressure distribution of the major frequency component in the system. The inlet section is indicated by the vertical line.

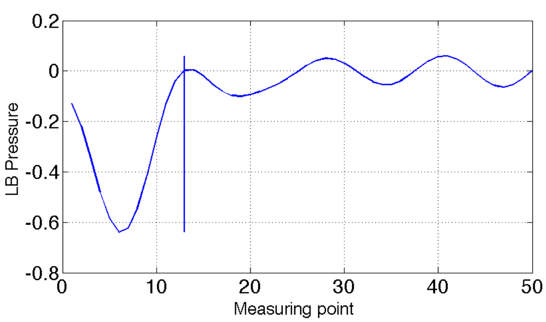

Figure 11: Pressure distribution of the second frequency component in the system.

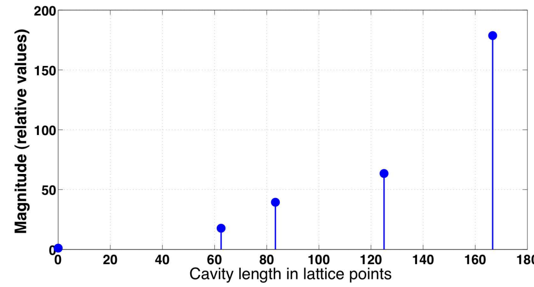

Figure 12: Relative values for the pressure magnitudes of the fundamental mode *vs* cavity length. The longest cavity corresponds to a physical length of 0.67 cm.

of vortices were found to be time synchronized with the pressure variations of the dominant acoustic mode. Due to the geometry of our system, presenting homogeneous boundary conditions to the acoustic field, the acoustic modes are artificial ones from a physical point of view. Nevertheless, we believe that such a model can be used to study the interaction between acoustic fields and air flow in pipe systems. Basic features found from the investigation were that the flow separates from the pipe walls at the entry surface of the pipe, and that there is a flow circulation in the cavity (when it is not too short). For one investigated geometry/flow situation it was seen that a vortex entering the cavity region was influenced by the cavity circulation and cut in two at the downstream cavity edge. From the acoustic investigation it was seen that the amplitude of the dominant mode would increase with the length of the cavity (for a limited parameter range). It was also observed that the second highest peak corresponds to a mode at a frequency near 20 times higher than the dominant one. As the results are promising, we want to continue investigating the influence of the different geometrical parameters on the aeroacoustic coupling. We should also investigate the possibility of creating acoustic dampers in the pipe upstream of the cavity pipe to possibly have more realistic boundary conditions. We would like the pipe having the cavity to exhibit its proper longitudinal pipe modes.

Lastly, we must bear in mind that the results represent calculations based on one particular numerical model. We must now seek validation of our results against further physical and numerical experiments.

References

[1] D. Mazzoni and U. Kristiansen, "Aeroacoustics of a flowpipe having a single small cavity " Proceedings of the Forum Acusticum 2011, Aalborg, Denmark 26 June - 1 July 2011 ISBN: 978-84-694-1520-7

[2] G. Nakiboglu "Aeroacoustics of corrugated pipes, chapter 5: Aeroacoustic power generated by a compact axisymmetric cavity". PhD thesis, Technical University of Eindhoven, 2012

[3] M. S. Howe Theory of vortex sound, Cambridge university press, 2002

[4] L. J. De Chant, "The venerable 1/7th power law turbulent velocity profile: a classical nonlinear boundary value problem solution and its relationship to stochastic processes." Applied Mathematics and Computation Vol. 161 pp 463 - 474 2005

[5] http://palabos.org/. Home page of the Palabos CFD Complex Physics project.

[6] H. S. Kook and L. Mongeau, "Analysis of the periodic pressure fluctuations induced by flow over a cavity," J. Sound Vib. 251, 823–846 (2002).

[7] M. S. Howe, "Mechanism of sound generation by low Mach number flow over a wall cavity," J. Sound Vib. 273, 103–123 (2004).

[8] J. C. Bruggeman, A. Hirschberg, M. E. H. van Dongen, A. P. J. Wijnands, and J. Gorter, "Self-sustained aero-acoustic pulsations in gas transport systems: Experimental study of the influence of closed side branches," Journal of Sound and Vibration Volume 150, Pages 371–393 (1991)

[9] P.A. Nelson, N.A. Halliwell, P.E. Doak "Fluid dynamics of a flow excited resonance, part I: Experiment " Journal of Sound and Vibration, Volume 78, Pages 15-38 (1981)

The films

Animated figure 2 (reduced velocity):
`../video/simulation2.mpeg`
Animated figure 3 :
`../video/simulation3.mpeg`
Animated figure 4 :
`../video/simulation4.mpeg`
Animated table 1 and 2 :
`../video/vorticity1.avi`
`../video/vorticity2.avi`